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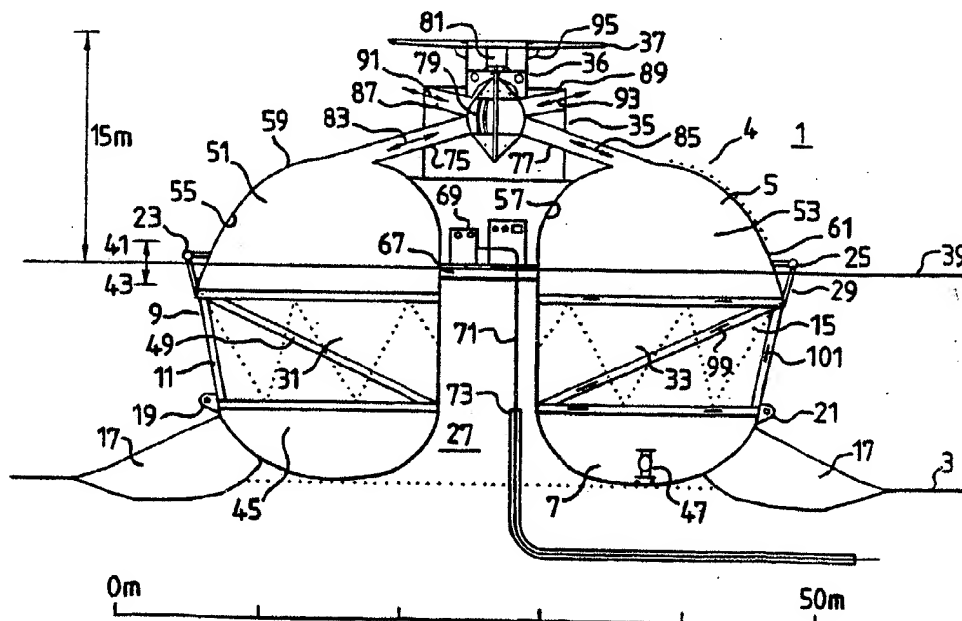
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(54) Title: COMBINED WIND AND WAVE POWER GENERATOR



(57) Abstract

Combined wind turbine and oscillating water column device with unidirectional rotation air turbine of the Darius type (79), both supported by the same offshore toroidal, polyhedral or quasi-spherical structure, anchored or otherwise fixed to the sea bed.

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COMBINED WIND AND WAVE POWER GENERATOR

The present invention relates to a converter for transforming natural energy into electrical energy.

Since the 1970's there has been increasing concern about the earth's finite fossil fuel resource and about environmental pollution resulting from combustion of such fuels. This has led to considerable efforts to develop new and cost-effective means of obtaining energy from renewable sources. In particular, there has been much interest in how to derive usable energy from solar, geothermal, wind and wave sources. The latter two offer the prospect of generating electricity by directly converting the kinetic energy of wind or waves into electrical energy.

Up to now, practical realisations of obtaining electrical power from wind energy have been land based, eg. in the form of so-called wind farms. However, these have a negative environmental impact. The wind generators are large and as well as being unsightly, they have been criticised for being noisy.

It would be more convenient if wind power generators could be located offshore. This would also be advantageous because generally, wind strength is greater over the sea or other large open bodies of water than over land.

Offshore, the wind generator would have to be floating (but anchored) or be supported on a structure, eg. resting on the sea bed. The cost for floatation or for a support structure would make offshore wind power units economically unviable.

On the other hand, waves theoretically constitute an enormous reservoir of energy to be exploited. However, their random nature and the hostility of the marine environment pose significant problems to the practical realisation of a cost-effective wave-to-electricity energy converter.

A limitation of wave power devices is that their electrical output is dependent on the amount of incident wave energy. In calm seas, the output may be well below optimum.

We have now overcome these drawbacks for both wind and wave generators by providing, in accordance with the present invention, an electrical generator comprising first means for converting wave energy to electrical energy and second means for converting wind energy to electrical energy, said first and second means sharing a common structure.

The effective cost of the floatation or support structure for the wind generator is less because the same structure also includes a wave power generator which produces electrical energy in its own right. This is especially so if the wind and wave units share common facilities, eg. transformer and land line link and other services and wiring.

The wind and wave units require means such as an alternator or dynamo for transforming the mechanical energy induced by wind and waves respectively, into electrical energy. Although they may each be provided with their own respective electrical generation systems, they could conceivably be linked to a single common alternator or the like.

Moreover, it is possible to use wind generators which

will operate in comparatively light breezes when the resultant swell is too low to produce an adequate output from the wave power generator.

The wind power unit preferably comprises an aero-generator, meaning any rotatable configuration, eg. propellor, turbine windmill etc capable of transforming the wind energy into rotary mechanical energy for in turn, driving the alternator or similar. The rotatable unit will generally comprise one or more blades which may extend in a substantially vertical plane or a substantially horizontal plane, or indeed at any appropriate angle depending on their type and the intended location.

Equally, the wave power unit may comprise any means for deriving electrical power from waves, provided that it shares a common structure with the wind unit. However, one preferred form of wave power unit is as described and claimed in our unpublished pending International Patent Application PCT/GB/00711. This wave power unit comprises several novel and inventive features. For convenience, any unit according to the aforementioned International Application is hereinafter termed "our preferred wave power unit".

Our preferred wave power unit may be provided with a wave collector comprising a substantially hollow annuloid shell having at least one opening for ingress of waves.

In use, the at least one opening of our preferred wave power unit is situated below the water so that waves entering through the opening impart their kinetic energy to the mass of air in the collector, above the water line.

The term "substantially hollow annuloid shell" is intended to refer to any closed substantially hollow structure which defines a substantially hollow core through the middle thereof. Thus, in radial cross-section, the outer and inner circumferences of the shell may be substantially circular, i.e. the shell is a true annulus or ring. However, annuloid structures which in radial section are elliptical, polygonal or any other closed hollow shape with a central core may also be used.

The shape of the core of our preferred wave power unit may be of any convenient kind, for example generally cylindrical. Although the core itself will usually be substantially hollow, in some embodiments it may be advantageous to locate some of the ancilliary equipment of the wave collector inside the core. Moreover, in many embodiments, the core will be open to the external environment at both ends thereof. However, the hollow core may also be substantially closed at one or both ends, provided that means are provided to enable water and/or air to enter and exit the core substantially freely.

It is especially preferred for stability reasons and for optimal wave tuning that the diameter of the annuloid shell is not substantially less than its height.

Overall, the annuloid configuration of our preferred wave power unit provides good stability whilst the collector is being towed in the water and when it is anchored in place for operation. At the same time, it provides an advantageous arrangement for the containment and ducting of the air which takes up the kinetic energy of the waves. The structure is also particularly cost-effective in terms of raw material and labour costs incurred during construction.

In axial cross section, the annuloid collector may also have any convenient shape, for example circular.

However, it is preferred that the collector of our preferred wave power unit should be generally toroidal, i.e. generally in the shape of a torus. A torus is an annular structure having a semicircular axial profile with the flat side of the semicircle facing inwardly towards the core.

It is particularly preferred that the collector is formed as an isotorus. An isotorus is a toroidal shell of uniform thickness having a modified circular cross-section so that it has constant axial membrane stress throughout. A common example of an isotorus is a pneumatic tyre having a small rim diameter.

Figure 3 of the accompanying drawings shows the general radial profile of an isotorus in a cartesian co-ordinate system. Closed solutions can be derived from the aforementioned requirement of constant axial membrane stress as follows: -

The reference radius of the isotorus, at which the walls are tangential to planes normal to the axis of symmetry, is considered to be R ; the internal pressure is p and the constant biaxial membrane force N /unit length. The inclination of the normal to the shell from the plane of symmetry is taken to be ϕ , and the Cartesian co-ordinates of the shell surface are described by x and y , where the x axis is the axis of symmetry. In consideration of axial equilibrium of the shaded volume it follows that, for meridional membrane force N ,

$$2\pi yN \cos\phi = \pi(R^2 - y^2)p, \quad \cos\phi = \frac{1}{2m} \left(\frac{1 - \beta^2}{\beta} \right) \quad (1)$$

where $\alpha = \frac{x}{R}$, $\beta = \frac{y}{R}$, $m = \frac{N}{pR}$. Solving for β , including the extreme values,

$$\beta = \sqrt{m^2 \cos^2\phi + 1} - m \cos\phi, \quad \beta_{\max, \min} = \sqrt{m^2 + 1} \pm m \quad (2)$$

In consideration of the hoop membrane force N it may be noted that the meridional and hoop radii of curvature r_1 and r_2 are given respectively by

$$\frac{dy}{\sin\phi \cdot d\phi} \quad \text{and} \quad y \sec\phi$$

The condition for equilibrium normal to the shell

surface, which is $p = \frac{N}{r_1} - \frac{N}{r_2}$, may then be written in the form,

$$\left(\frac{1 + \beta^2}{2\beta^2} \right) d\beta = m \sin\phi \cdot d\phi,$$

or by integrating,

$$\cos\phi = \frac{1}{2m} \left(\frac{1 - \beta^2}{\beta} \right) \quad (3)$$

as in equation (1). The shell is thus proven to exhibit constant biaxial membrane forces throughout.

For the determination of α and x it is first noted that (using equation (2)),

$$\frac{d\alpha}{d\beta} = \cos \phi, \text{ so that}$$

$$\alpha = \int_0^\phi m \cos \phi \left(1 - \frac{m \cos \phi}{\sqrt{m^2 \cos^2 \phi + 1}} \right) d\phi =$$

$$m \sin \phi - \frac{m^2}{\sqrt{m^2 + 1}} \int_0^\phi \frac{\cos^2 \phi \cdot d\phi}{\sqrt{1 - \frac{m^2}{m^2 + 1} \sin^2 \phi}} = \quad (4)$$

$$m \sin \phi - \left[\sqrt{m^2 + 1} E \left(\phi, \frac{m}{\sqrt{m^2 + 1}} \right) - \frac{1}{\sqrt{m^2 + 1}} F \left(\phi, \frac{m}{\sqrt{m^2 + 1}} \right) \right]$$

(5)

as collated by H B Dwight, Tables of integrals and other mathematical data, McMillan, NY, 1961, case 782.01.

$E()$ is the elliptic integral of the second kind, and $F()$ the elliptic integral of the first kind. Both are tabulated from $\phi = 0$ to $\frac{\pi}{2}$ in Jahnke-Emde, Tables of functions, Dover, 1945. For values of $\phi \geq \frac{\pi}{2}$ the property of antisymmetry of the functions $E()$ and $F()$ may be taken into consideration, arising from the nature of the integrals.

It may also be demonstrated by reference to equation (2) et seq, by differentiation, that the meridional radius of curvature is,

$$\frac{r_1}{R} = m \left(1 - \frac{m \cos \phi}{\sqrt{m^2 \cos^2 \phi + 1}} \right) = \frac{2m\beta^2}{1 + \beta^2} \quad (6)$$

with the extreme values

$$m \left(1 \pm \frac{m}{\sqrt{m^2 + 1}} \right) \quad \text{at}$$

$$\phi = 0, m \left(1 + \frac{m}{\sqrt{m^2 + 1}} \right) \text{ at } \phi = \pi, \text{ the value } m \text{ at } \phi = \frac{\pi}{2} \text{ with a}$$

continuous increase from intrados to extrados.

For the normal torus of major radius r and minor radius ρ the largest stress under pressure p is meridional at the intrados, with the value

$$N = \frac{p\rho}{2} \cdot \frac{2r - \rho}{r - \rho} \quad \text{For comparison with the isotorus the non-dimensional}$$

values $r = \sqrt{m^2 + 1}$, $\rho = m$ are substituted, whence the ratio of the maximum pressure stresses in the isotorus and normal torus becomes,

isotorus uniform pressure stress

Ratio: normal torus maximum pressure stress

$$= \frac{\sqrt{m^2 + 1} - m}{\sqrt{m^2 + 1} - \frac{m}{2}}$$

(7)

with the value 0.453 for $m = 1$.

Table 1 shows isotorus shape factors for several values of m ; Figure 3 of the drawings shows a graphical representation for the same values of m . The negative values of α at $\phi = \pi$ may be noted, which indicate the differing cross-sections of the torus and isotorus.

TABLE 1

| m | $m^2 + 1$ | $\frac{m}{\sqrt{m^2 + 1}}$ | $\frac{\sqrt{m^2 + 1} - m}{\sqrt{m^2 + 1} + m}$ | $\phi = 0$ | $\frac{\pi}{4}$ | $\frac{\pi}{2}$ | $\frac{3\pi}{4}$ | π |
|-----|-----------|----------------------------|---|---------------|-----------------|-----------------|------------------|--------|
| 0.5 | 1.1180 | 0.4472 | 0.712 | E() 0 | 0.771 | 1.489 | 2.206 | 2.977 |
| | | | | F() 0 | 0.800 | 1.660 | 2.520 | 3.320 |
| | | | | α 0 | 0.207 | 0.321 | 0.141 | -0.359 |
| | | | | β 0.618 | 0.707 | 1 | 1.414 | 1.618 |
| 1 | 1.4142 | 0.7071 | 0.453 | E() 0 | 0.748 | 1.351 | 1.953 | 2.701 |
| | | | | F() 0 | 0.826 | 1.854 | 2.882 | 3.708 |
| | | | | α 0 | 0.233 | 0.401 | -0.0168 | -1.198 |
| | | | | β 0.414 | 0.518 | 1 | 1.932 | 2.414 |
| 2 | 2.2361 | 0.8944 | 0.191 | E() 0 | 0.724 | 1.179 | 1.633 | 2.357 |
| | | | | F() 0 | 0.857 | 2.261 | 3.665 | 4.522 |
| | | | | α 0 | 0.178 | 0.375 | -0.598 | -3.248 |
| | | | | β 0.236 | 0.318 | 1 | 3.146 | 4.236 |

Preferably, in our preferred wave power unit, one opening in the shell for ingress of waves extends completely around the outer circumference. Both such openings preferably also extend from just above half the height of the collector, but still below the intended sea level, down to approximately one quarter of the height. Above and below the opening(s), the shell then effectively comprises an upper canopy and a lower canopy, respectively. The two canopies are kept apart by a cage structure consisting of struts which impart the necessary strength and rigidity but otherwise allow sea water to pass therebetween. The overall shape of the isotorus shell is best understood by reference to Figures 8-10 which show an embodiment of our preferred wave power unit, based on the isotorus and described in detail hereinbelow.

Our preferred wave power unit may be provided with a wave collector comprising a generally hollow canopy having at least one opening for ingress of waves, said canopy having an internal datum level defining a median water level when in use, said at least one opening defining a water inlet area, wherein the ratio of the internal cross-sectional area of the canopy at the internal datum level to the water inlet area being less than 0.7.

The area of the at least one water inlet area means the total surface area of all such inlets in a given canopy.

Preferably the ratio is less than 0.6, especially less than 0.5 but preferably more than 0.4.

It is also preferred that the generally hollow canopy has a substantially hollow profile.

Such a spherical profile canopy may be substantially

perfectly spherical in shape or approximately spherical. Moreover it may be in the form of a complete sphere or complete approximate sphere (except for any openings therein) or it may be a truncated sphere or truncated approximate sphere.

A particularly preferred form of such a wave collector is termed herein, a "sphere-polyhedron collector". This is conveniently described by reference to an especially preferred form thereof, hereinafter called a "three cell sphere-tetron collector". Tetron is an abbreviation of inflated tetrahedron.

In general, the sphere-polyhedron configuration comprises a substantially spherical profile canopy having an inflated polyhedral internal shell. In use, the collector is embedded in the sea-bed (or similar) sediment and the canopy is part-filled with sediment to substantially the level of the external bed or higher. The sediment base may then constitute one side of a polyhedron shape. Conveniently, one vertex of the inflated polyhedron as located at the top of the spherical canopy.

Any reference herein to a polyhedron or an inflated polyhedron includes both a substantially perfect polyhedron or substantially perfect inflated polyhedron, and an approximate polyhedron or approximate inflated polyhedron. The terms "polyhedral" and "inflated polyhedral" are to be construed likewise. By "inflated" is meant having outwardly curved sides.

At least one cut-away portion of the canopy defining a circular or part-circular opening abutting a side of the base of the inflated polyhedral internal shell, is provided for ingress of waves. Most preferably, a plurality of such openings are provided, respectively

abutting each of the sides of the base of the internal shell along straight sides of the openings.

The overall shape of the especially preferred three cell sphere tetron-collector is best understood by reference to Figures 13 and 14. These show one form of our preferred wave power unit based on the latter collector shape and described in more detail hereinbelow.

Alternatively, a variant of the three cell sphere tetron-collector may be fabricated for deep water applications. Instead of the inflated tetrahedron internal shell, a conical or frustoconical internal shell may be provided. Conveniently, this conical or frustoconical shell may be slip-formed from concrete. This variant is not limited to provision of three cells but fewer and more cells are also possible.

Since the internal shell of these sphere-polyhedron (and variant) collectors defines a substantially hollow core, albeit closed at the top, such collectors are also possible.

The characteristics of the three cell sphere-tetron collector in comparison with the isotorus shape are as follows: -

1. proportionately larger entry/exit cross-sections for wave motion, extending nearly to the seabed, hence improved hydraulic efficiency;
2. up to 25% increase of fully enclosed sediment mass;
3. a broader base, with adequate stability against overturning,
4. unimpaired structural support for the turbo generator housing, and comparable pneumatic flow paths;

5. easier construction with modular fore fabrications (less plate waste; less weld lengths);
6. reduced steel mass (-30%) for given service stresses (smaller plate thicknesses; reduced weld deposit volumes), and
7. stabilisation required for seabed sediment only; much less stone armour (referred to hereinbelow) being required only under the cone vertices.

With our preferred wave power unit, to optimise air flow patterns above the water line for efficient driving of a rotor coupled to a generator, the upper canopy area is preferably divided into a plurality of cells by a plurality of radial dividers. These dividers prevent air flow from one cell to another. Therefore, the lower edges of the dividers extend below the water-line. If appropriate, these lower edges conveniently may extend diagonally inwards and downwards to traverse the opening(s) in the shell. In other configurations, it may be preferred to provide respective separate openings in the canopy for each of the cells.

It is envisaged that in most collectors having a hollow annuloid shell, at least two radial dividers/cells would be provided, or alternatively, from three to five. Three dividers/cells are especially preferred for collectors according to the second aspect of the present invention. In most applications, all such dividers would probably be arranged with comparable radial spacing.

As well as the wave collector, our preferred wave power unit must comprise means for converting the kinetic energy of the moving air into electrical energy. Whilst this may be achieved using any suitable technology which will be apparent to those skilled in the art, conveniently it may be effected by means of a rotor

arranged to drive a generator.

Preferably, the generator and rotor are arranged in a housing located centrally above the collector. Ducts must be provided for conveying the air from the collector to the rotor in the housing.

One preferred form of rotor for this application is the so-called Darius rotor. Essentially, the Darius rotor comprises a plurality of aerofoil-shaped blades, preferably of symmetric cross-section, extending longitudinally between an upper and a lower support so as to form a pseudo-spherical cage.

The aerofoil-shaped blades provide radial lift with a circumferential component of torque, always in the direction of the leading edges, irrespective of inward or outward radial airflow. Therefore, if a plurality of ducts convey air from cells of the collector, no matter in which direction the air is flowing in each duct, it will always impart rotational motion in the same direction to the rotor. Therefore, these airflows cannot effectively cancel one another in terms of their action on the rotor.

The Darius rotor has previously only been used unenclosed for windmill applications. The arrangement of a Darius rotor in an enclosed housing communicating with air ducting demonstrates synergy by virtue of the resultant reciprocating multi-phase airflow. The arrangement provides a more uniform torque when fully utilising the quadrature wave components of heave and surge induced pitch, thereby extracting much more of the available power from each wave.

Thus our preferred wave power unit may comprise a wave energy converter comprising a Darius-type rotor arranged

in a housing provided with at least one opening for directing an oscillating air flow onto or away from the rotor in an axisymmetric manner, wherein the rotor comprises a plurality of blades in a substantially catenary shape such that centrifugal loads are substantially balanced by blade tension-forces.

In the context of the present invention, the term "Darius-type rotor" means a plurality of spaced, substantially constant cord and substantially zero incidence aerofoil blades in cage structure formation and substantially axially aligned relative to an axis of rotation so that radial fluid flow into and out of the cage structure causes the structure to rotate about said axis. Generally, the resultant rotation will occur at a substantially constant peripheral speed with respect to the exposed length of each blade.

The advantage of this configuration is that in principle, it can provide four times the power, for a given diameter, tip speed and blade/space ratio (solidity) compared with a single plane rotor. Conveniently, the blades are supported in tension with respect to centripetal forces by adopting the catenary form, so that approximately one rotor radius of blade length is exposed to radial airflow. Therefore the cage structure form is preferably identical to, or as closely approximate to this shape as is feasible.

The above definition of the Darius-type rotor indicates the essential geometry of the blades in the cage structure in the region of intended incident flow. Any suitable configuration may be employed in the region where the blades are attached to the aforementioned upper and lower supports.

It is especially preferred that the blades are

substantially uniformly spaced within the cage structure. Preferably, the number of blades incorporated in the cage structure is from 3 to 25, for example from 5 to 20, more preferably from 9 to 15.

However, the optimum number in any given application will depend on the overall size of the structure, the power of the incident flow and the characteristics of the associated generator.

A variant of the Darius rotor is described in UK Patent Specification GB 1 595 700. The radial (Darius) and axial (variant) directions are interchanged. The variant is described as located in a housing for direct conversion of wave energy. As mentioned above, the Darius-type rotor has not previously been described mounted in a housing for conversion of wave energy transmitted via air movement.

In the high speed pneumatic application herein described, as compared with the variant, the Darius-type configuration not only retains efficient blade support with similar maximum centrifugal stresses, but has the additional advantages: -

1. more uniform peripheral velocity distribution,
2. two stages as an intrinsic property to improve power density at the lower solidities desirable for high efficiency operation.

The housing of the Darius-type rotor preferably has a plurality of openings. Most preferably, at least two openings are provided for transmission of air to and from the wave collector and one or more additional openings communicate with the outside atmosphere.

Most preferably, the rotor is a substantially classical Darius rotor per se. Figure 5 shows the generalised shape of the blades Darius rotor in a cartesian co-ordinate system. In use, there would be a plurality of such blades arranged uniformly around the x axis so that the rotor would rotate around the x axis as shown by the symbol ω .

Centripetal accelerations are radial, whence for this case $P = P_i \sec \theta$. For mass w per unit length, $w\omega^2 y ds \cos \theta = P_i d\theta$.

$$\frac{d\theta}{dx} = \frac{w\omega^2}{P_i} y \cos \theta \quad (8)$$

Lift normal to aerofoil is $\pi c_p w v$, and tension is uniform with respect to s in this case. Whence, $\pi c_p w v y \cos \theta ds = P_i d\theta$

$$\frac{d\theta}{dx} = \frac{\pi c_p w v}{P_i} y \quad (9)$$

If aerofoil is braced to this profile by distributed wires normal to the aerofoil in the radial plane, oscillating lift forces will cause no vibration as rotation occurs, and constant tension will be maintained with regard to centripetal accelerations. Similarly, there will be no vibration if, from equation 8, $w = w_i \sec \theta$, and the initial profile satisfies equation 9. Putting equation 9 into the form $\frac{d\theta}{dx} = Ay$,

differentiating with respect to x , and noting that

$$\frac{dy}{dx} = -\tan \theta, \text{ gives } \frac{d^2\theta}{dx^2} = -A \tan \theta.$$

Now putting $p = \frac{d\theta}{dx}$, it follows that

$$\frac{d^2\theta}{dx^2} = \frac{dp}{dx} = \frac{d\theta}{dx} \frac{dp}{d\theta} = p \frac{dp}{d\theta} = -A \tan \theta$$

Then

$$p \cdot dp = -A \tan \theta d\theta, \quad \text{and} \quad \frac{p^2 - p_0^2}{2} = A \ln \cos \theta.$$

Whence, since $p_0 = \frac{1}{R_0}$,

$$\frac{dx}{R_0} = \frac{d\theta}{\sqrt{1 + m \ln \cos \theta}}, \quad \text{where } m = \frac{2\pi c p \omega v R_0^4}{P}, \quad \frac{dy}{R_0} = -\frac{dx}{R_0} \tan \theta$$

$$\left[\text{Also, } m = \frac{2R_0}{r} \right]$$

(10)

These may be integrated numerically to derive x and y for increments of θ for various specified values of the constant m . Some ideal Darius rotor shapes for different values of m are shown in Figure 4.

In addition the swept area factor is $\frac{1}{R_0^2} \int_0^\theta y dx$, and the torque factor is

$$\frac{1}{R_0^2} \int_0^\theta y \cos \theta dx. \quad \text{More conveniently, put}$$

$$\frac{1}{r^2} \int_0^\theta y dx = \alpha, \quad \frac{1}{r^2} \int_0^\theta y \cos \theta dx = \beta, \quad \text{where } r \text{ is the radius at } \theta = 0,$$

R being the radius of curvature. For incident wind velocity v the reference work rate per unit of swept area is $\frac{16}{27} \cdot \frac{\rho v^3}{2}$. Hence, total work rate E given by,

$$E = \frac{16}{27} \frac{\rho v^3}{2} 4\alpha r^2 \quad (11)$$

The tangential driving force per unit length of aerofoil of constant chord c is

$\pi c r v^2$. Hence the average torque for n blades is

$$T = n \pi c r v^2 \beta r^2 \quad (12)$$

But angular velocity $\omega = \frac{V}{r}$ at maximum radius, and $\frac{V}{v} = 2\pi$ for unit lift coefficient. Since $T\omega = E$ by equating 11 and 12,

$$\frac{n c}{r} = \frac{32}{27 \pi} \frac{v}{V} \frac{\alpha}{\beta} = \frac{16}{27} \frac{C_L}{\pi^2} \frac{\alpha}{\beta} \quad (13)$$

Also, $P_t = w \omega^2 R r$, $P = \pi c p \omega v R r$, (also stress $\sigma_t = \frac{m \gamma v^2}{2}$ from centripetal acceleration). (14)

P_t is always tension, but P alternates in sign. For limiting case of zero P_t , $-P$, and no compression, from (13 and 14),

$$\frac{k \gamma}{\rho} \geq \frac{27 n \pi^2 \beta}{32 \alpha} \quad (15)$$

where $w = k \gamma c^2$ and γ is aerofoil density; k is a shape factor.

Figure 5 illustrates operation of the Darius Rotor in Axi-symmetric flow.

For zero incidence, the average tip speed V and inflow velocity v , the lift coefficient $C_L = \frac{2 \pi v}{V}$ and for chord c the lift/unit length is $\pi c p v$, where

fluid density is ρ . For average radius r , the torque/unit length = $\pi c r p v^2$.

For n blades, each of effective length $2kr$ the total torque is $2 k n \pi c r^2 p v^2 = 4 \pi^2 k \alpha r^3 p v^2$, where $\sigma = \frac{n c}{2 \pi r}$ is solidity. Power E , obtained by multiplying by ω and substituting for v in terms of C_L and

$V = \omega r$, is

$$E = k\sigma C_L^2 \rho \omega^3 r^5 \quad (16)$$

By definition, the inflow is $2\pi k r^2 v = k C_L \omega r^3$, which may be divided into equation 16 to obtain the pressure difference. Thus, in terms of head h , for the two stage device, it is verified that,

$$h = \frac{\sigma C_L \omega^2 r^2}{g} \quad (17)$$

Given E and h , r and σ may be obtained from equations 16 and 17 as,

$$r = \left[\frac{E}{k C_L \omega \rho g h} \right]^{\frac{1}{3}} \quad \sigma = \left[\frac{k^2 \rho^2 g^5 h^5}{C_L \omega^4 E^2} \right]^{\frac{1}{3}} \quad (18)$$

Equations 18 can be used to calculate rotor radius and the product of blade chord and number of blades in terms of the solidity ratio σ .

Examination of equation 15 emphasises the importance of using steel for the blades, in order that vibrations and lift induced fatigue stress effects should be minimised.

The consequence in terms of equation 14 is that centrifugal stresses, at 380 N/mm^2 for steel are well within the strength ($< 1/4$) of steel wire, such as is used for concrete prestressing. Moreover, the standard conical wedge grip for prestressing tendons is well developed, efficient, trustworthy and can be densely packed.

The best form of blade construction would then be a parallel group of such wires in a g.r.p. matrix.

However, for cost effectiveness reasons, it is preferred that the individual rotor blades comprise short glass fibre loaded polyethylene extruded to aerofoil section around a longitudinal matrix of high strength steel wires, each about 5mm diameter. The ends of these protrude beyond the polyethylene, and are located in conical holes in the upper and lower supports referred to above. These ends are wedge gripped in the holes with a standard, compact tool as used for post tensioning of steel wire tendons in concrete. The effect of centripetal force is to place the blades in tension, and their slight flexibility permits them to take up the rotor shape. The shape $m = 2$ is most preferred in terms of a well maintained blade radius over the operative region, without lengthening the shaft so as to detract from its resistance to axial load and whirling collapse.

In either case, the structure can be towed to the chosen marine site and anchored to the seabed by weighting of the lower canopy area.

The structure may be anchored to the bed of the sea or other body of water in or with sediments on the bed. It could also be mounted on a concrete base on the bed.

Preferably, in the former case, the sediments used for the anchoring are treated, eg. chemically, to at least partly stabilise them.

The sediments may be pumped into the structure to lie in the lower part thereof. The sediments may also, in addition or in the alternative, be heaped up around the base of the structure. Again, in addition or in the alternative, the structure may be embedded in the sediments.

Only an upper region, eg the top surface, of these sediments may be treated or they may be treated substantially throughout.

In the case of the preferred form of wave collector having a lower canopy area, sediment is pumped into the latter and permeated with lime water and carbon dioxide so that it is stabilised. Lime water and carbon dioxide constitute a particularly preferred treatment for any application. This may also be done with other structures. Other forms of structure or wave collectors may, for example, be embedded in the sediment and the sediment immediately surrounding the structure can then be chemically treated.

Other particular forms of chemical treatment are also possible. For example, the sediment may be permeated with sodium silicate and hydrochloric acid which react chemically to form silica gel. The latter in combination with the sediment then effectively form a stable base. It is also possible to permeate the sediments with an oil such as residual oil to achieve the same effect. Another treatment is to permeate the sediments with portland cement grout.

The ultimate choice of material(s) for this chemical or other treatment will ultimately depend on the logistics of supply and placement, as well as cost and environmental considerations.

It is also possible to place broken rock around the outside of the structure when it is anchored in place.

Returning once again to our preferred wave power unit, it may have a canopy divided into a plurality of cells, eg. by one or more internal walls. The oscillating water surface level in a given cell will not usually be completely in phase with the oscillation in another

cell. This effect may be utilised to smooth energy conversion rate with respect to time.

Thus, our preferred wave power unit may also have a generally hollow canopy having at least one opening, said canopy being divided internally into a plurality of cells, at least two of said cells having internal dimensions different from each other such that the ratio of median waterline cross-sectional area of one of said at least two cells to the median waterline cross-sectional area of the other is in the range of from 3:1 to 1:3.

It is especially preferred that this ratio is substantially 2:1.

The median waterline is the level inside the canopy corresponding to the average water level during use.

This arrangement is intended to cause a substantially phase quadrature difference between the water levels in the respective at least two cells at any one time.

In use, an electrical generator according to the present invention may operate in cooperation with one or more other generator units located in the same vicinity. These other units may independently be electrical generators according to the present invention or wave power generators only, i.e. lacking wind units.

Any electrical generator according to the invention may also be provided with other advantageous features such as means enabling vessels to moor alongside, or a helicopter landing platform, or overhead cableway ashore.

The present invention will now be illustrated by way of the following description of a preferred embodiment and

with reference to the accompanying drawings, in which: -

Figure 1 shows a side view of an electrical generator according to the present invention;

Figure 2 shows a front view of the generator shown in Figure 1;

Figure 3 shows a graphical representation of the radial profile of an isotorus shell of a wave collector for use in a generator according to the present invention;

Figure 4 shows some different solutions for radial profiles derived with reference to Figure 3;

Figure 5 shows a graphical representation of a Darius rotor blade for use in a wave power unit which may form part of a generator according to the present invention;

Figure 6 shows some different solutions for rotor shapes derived with reference to Figure 5;

Figure 7 shows a graphical representation of a Darius rotor in axi-symmetric flow;

Figure 8 shows a side view of a wave energy converter with an isotorus collector for use as part of a generator in accordance with the present invention;

Figure 9 shows an axial cross-sectional view through the converter shown in Figure 8;

Figure 10 shows the Darius rotor of the converter shown in Figures 8 and 9, together with associated components;

Figure 11 shows a cut-away perspective view the Darius rotor shown in Figure 10, with baffle plates for directing air into and out of the ducts;

Figure 12 shows a radial cross-section through the centre of the Darius rotor shown in Figures 10 and 11;

Figure 13 shows an outline perspective view of a wave energy converter with a three cell sphere tetron-collector which may form part of a generator according to the present invention;

Figure 14 shows the arrangement of cell dividers in the convertor shown in Figure 13;

Figure 15 shows a radial cross-section through another collector for a wind power unit of a generator according to the present invention, having a cell divider arrangement for effecting phase quadrature between water levels in adjacent cells;

Figure 16 shows an axial cross-section through the collector shown in Figure 15; and

Figure 17 shows a method of anchoring an electrical generator according to the present invention or part thereof.

Figures 1 and 2 show an electrical generator 301 according to the present invention. It comprises a wind power unit 303 for converting wind energy into electrical energy and a wave power unit 305 for converting wave energy into electrical energy. The wind power unit is mounted on top of the wave power unit by means of a support structure 307.

The wind power unit is provided with a two-blade rotor 309, the blades 311, 313 of which are arranged to rotate in a vertical plane.

The wave power unit is anchored to the sea bed 315 and partially protrudes above the mean sea level 317. The wave power unit is essentially as shown in Figures 15 and 16 and will be described in more detail herein low.

Other forms of wave power unit and parts thereof which may be used instead are shown in Figures 8-14 and 17. For convenience, the wind-power unit is not shown in the latter figures but the description should be interpreted so that the wind power unit is present, mounted on top of the respective wave power unit. Where shown, any helicopter landing platform may be excluded if it would

interfere with mounting of the wind power unit.

Thus, Figure 8, shows an alternative wave power unit 1 to be used in place of the wave power unit 305 in the structure shown in Figures 1 and 2. This structure is anchored to the sea bed 3 by stabilised sediment in a manner to be described hereinbelow. It comprises a shell 4, an upper canopy 5 and a lower canopy 7, separated by a cage structure 9 comprising struts 11, 13 etc. The separation effected by the cage structure defines an opening 15 for ingress of waves.

Anchoring the sea bed is further aided by approximately 6000 cubic meters of dumped stone armour 17 surrounding the lower canopy. Towing pad eyes 19, 21 are provided to enable the structure to be towed into position. Barge bumpers 23, 25 enable service vessels to moor alongside.

The hollow central core 27 of the isotorus wave collector 29 is visible through the opening 15, as are radial dividers 31, 33. The top of a rotor housing 35 extends above the upper canopy and is surrounded by a generator housing 36 and a helicopter landing platform 37.

When correctly installed on-site, the opening 15 is situated below sea-level 39.

The structure shown in Figure 8 is depicted in axial cross-section in Figure 9. Relevant components are designated by the same reference numerals. The overall dimensions of the structure are shown in this Figure. It is designed to operate with a maximum wave amplitude between maximum level 41 and minimum level 43.

The lower canopy contains approximately 4200 cubic

metres pumped fill sediment 45 introduced and stabilised by chemical treatment (to be described hereinbelow) via a flooding control valve 47. A tubular steel frame 49 supports the radial dividers 31, 33 which respectively form one boundary of a pair of cells 51, 53. The peripheries 55, 57 of the dividers abut the respective cell walls 59, 61 which are integral with the upper canopy, except the lower edges 63, 65 thereof which are attached to the tubular frame and transverse the opening of the shell, extending inwardly and downwardly.

A pressure bulkhead 67 extends across the central hollow core, above which is situated control equipment 69 which transfers electrical energy generated by the converter to a subsea cable 71 which connects with the shore via piped cable duct 73 extending beneath the seabed.

The cells communicate via ducts 75, 77 with the housing 35 in which is located a Darius rotor 79 which is attached to a generator 81 in the housing 36. Alternatively, first and second Darius rotors may respectively be fixed to opposite ends of the shaft driving the generator, for receiving/delivering air to two respective cells.

In use, in response to changes in water height, due to waves, air flows between the cells and rotor via the ducts 75, 77 in both directions as indicated by arrows 83, 85 and between the rotor and the external atmosphere via further ducts 87, 89 in both directions as indicated by arrows 91, 93. As explained hereinbefore, the rotor turns in the same direction, regardless of the direction of airflow.

A navigation beacon 95 is attached to the outside of the generator housing, directly underneath the helicopter landing pad. Clambering rings 97, are attached to the

outside of the upper canopy to permit access to and from any vessel moored alongside. Sacrificial anodes 99, 101 are attached to the cage structure and tubular steel support frame to prevent corrosion.

The arrangement of the Darius rotor, together with the ducts and generator is shown in Figure 10. The scale is shown below the drawing.

The rotor comprises a plurality of aerofoil blades 103, 105 etc extending between an upper support 107 and a lower support 109 mounted on a shaft 111. The blades thus constitute a "squirrel cage" structure. The shaft is connected to the generator 81 via a coupling 113. The generator is mounted on a support frame 115.

The precise number of blades, together with their aerofoil surface profile, shape of curvature and overall size are determined as described hereinbefore. The central portion of the blades approximately follows the curvature of a nominal sphere shown by the broken line 117.

An upper drop gate 119 both controls power output from heave and seals the pneumatic turbine (rotor and generator) against entry of water when overtopped. In the closed state, the generator is able to operate at full power by continued extraction of surge and pitch power. Lowering the drop gate beyond midstroke permits control of power extraction and in the limit effects shutdown in the event of any electrical or mechanical fault.

As shown in Figure 11, upper 117, middle, 119 and lower 121 baffle plates (shown partly cut-away) are provided for directing airflow into and out of the ducts 75, 77, 87, 89. Obviously, the rotor must be able to rotate

freely inside these plates.

The cross-section view through the central radial plane of the rotor as illustrated in Figure 12 shows the aerofoil profile of the blades. As depicted, the rotor will rotate anti-clockwise as air flows into and out of the rotor cage structure.

Figures 13 and 14 show another form of a wave energy converter to be used in place of the wave power unit 305 shown in Figures 1 and 2. This is based on a three cell sphere-tetron collector in place of the isotorus collector as shown in Figures 8 and 9. The same reference numerals are used for the sea surface, sea-bed, stone armour and the rotor/generator structure, as are used in the latter two Figures.

The converter comprises a collector having a truncated spherical canopy 123 partly embeded in the sediment on the sea bed. An inflated tetrahedral internal shell 125, concentric within the sphere, is defined by three outwardly curved downward extensions 127, 129, 131 which engage with the three lower vertices 133, 135, 137 of the tetrahedron, respectively. The fourth vertex 139 is located at the top of the collector, adjacent the rotor and generator. The base 140 of the tetrahedral core is defined by three substantially straight horizontal members 141, 143, 145.

The lower part of the spherical canopy is filled with sediment at least up to the level of the surrounding sea bed, or more preferably, to the level of the base of the tetrahedral frame and surrounding stone armour 17. Further details concerning the method of anchoring are recited hereinbelow.

The radial plane interstices between the canopy and

edges of the inflated tetrahedron are occupied by divider plates 147, 149, 151 to define three cells 153, 155, 157. Ducting of airflow between the cells and rotor and between the rotor and the exterior is analogous to that used in the previously described isotorus form.

Partly circular openings 159 etc (eg. semicircular or 1/3 circular) are provided in the canopy, positioned to be abut the base sides of the tetrahedron. These openings permit ingress and egress of waves. The wave energy converter otherwise functions in an analagous manner to the isotorus form.

In essence, the inflated tetrahedral frame consists of four 60° cones with axes intersecting, so as to acquire the necessary "inflated" shape giving excellent internal pressure strength, (this may be demonstrated by inflating a rectangular paper or polyethylene bag).

The connection between sphere and frame may be envisaged with the aid of an imaginary cube, with one point uppermost, so that diagonals of the six faces form the edges of the tetrahedron. The uppermost three faces of the cube then locate the concentric canopy surface at seven points of the cube, so as to become curvilinear square. The latter may be uniformly subdivided by equi-spaced great circles and circles of latitude, and are fabricated from edge profiled, but jointed strips of plating of approximately uniform widths.

Anchorage of these structures by stabilised sediment fill will now be described in more detail.

The structure of any generator, with or without the wind power unit-already attached, may be floated light from the construction site in less than 2 metres of water,

with ample freeboard for towing and high stability. After it is floated above the bed for final location and has been flooded, air is bled from the upper canopy area so that it sinks quickly. Slight wave induced vertical oscillations when floating above the site assist formation of an initial bed. The lower canopy is then pump filled with sediment to provide gravity anchorage. The sediment fill is then permeated with lime water and carbon dioxide, or with any other suitable stabilising chemical treatment. If the wind power unit is not already attached to the wave unit, it may be done at this stage.

Using the lime-water and carbon dioxide system for filling the pore space in the sediment reduces permeability. It does not, and there is no need for it, to induce cohesive strength. The chalk precipitated by the resultant chemical reaction has a measured brittle strength ranging from that of kettle fur deposits to stalactite, depending on the rate of deposition.

In practice, an effective generating station may comprise a plurality of wave energy converters spaced apart at suitable intervals, for example in a linear arrangement, at a location where the incident wave power is at an appropriate level.

Referring now to Figures 15 and 16, the configuration of wave power unit 161 is essentially that of the generator shown in Figures 1 and 2. The only difference is that in Figures 1 and 2, the upper portion of the canopy is not tilted relative to the lower.

This kind of construction generally exemplifies the kind of structure in which the ratio of the internal cross-section area of the canopy at the internal datum

level is less than 0.7 and/or the ratio of median waterline cross-sectional area of one of the cells to that of the other is in the range of from 3:1 to 1:3.

The wave power unit of Figures 15 and 16 is arranged to collect waves W from the right-hand side of the drawings.

This wave power unit has a collector comprising a canopy 163 having an upper portion 165 and a lower portion 167 separated by a tapering opening 169 which is wider at the front 171 facing the waves W than the at rear 173 on the opposite side.

The two opposing rims 175, 177 of the respective upper and lower portions defining the opening are provided with respective channels 179, 181 which are tear-drop shape in cross-section. These channels assist ingress of water they have internal aerofoil shaped supporting struts 183-197.

A central tower 199 is provided with a generator 201, a pair of Darius rotors 203, 205 on opposite ends of a shaft driving the generator.

The canopy is divided by an arcuate cell divider 207 into a larger cell 209 at the rear and a smaller cell 211 at the front facing the waves. The ratio of radial cross-section (Fig. 13) cross-section area of the larger cell 209 to that of the smaller cell 211 is approximately 2:1.

Figure 15 shows details of how a wave collector 213 is anchored on the sea bed 215. The wave collector canopy 217 extends above the water-line 219. The collector rests on a support structure 221. Again, the wind power unit may already be attached or that may be done after anchoring.

A ship 223 is equipped with a high pressure water pump and tank 225 which is connected via line 227 to a sub-sea connector 229. A high pressure water hose 231 provided with a terminal suction head 235 pumps sediment 237 via a delivery hose 239 into the support structure via the open end 241 of the hose.

If necessary the same hose can be used to deliver chemicals to the pumped sediment to stabilise it.

In the light of this disclosure, modifications of the described embodiments as well as other embodiments, all within the scope of the present invention as defined by the appended claims will now be apparent to persons skilled in the art.

CLAIMS

1. An electrical generator comprising first means for converting wave energy to electrical energy and second means for converting wind energy to electrical energy, said first and second means sharing a common structure.
2. A generator according to claim 1, wherein each of said first and second means comprises an alternator or dynamo for transforming the mechanical energy induced by wind and waves respectively, into electrical energy.
3. A generator according to claim 1, wherein said first and second means are linked to a single common alternator or dynamo.
4. A generator according to any preceding claim, wherein said second means comprises an aero-generator.
5. A generator according to claim 4, wherein the aero-generator comprises one or more blades.
6. A generator according to claim 5, wherein said aero-generator comprises a plurality of blades each extending in a substantially vertical plane or a substantially horizontal plane.
7. A generator according to any preceding claim, wherein said first means is configured to define a body of air which in use oscillates in response to wave motion, the oscillation causing rotation of a turbine.
8. A generator according to any preceding claim, wherein said first means is provided with a wave collector comprising a substantially hollow annuloid shell having at least one opening for ingress of waves.

9. A generator according to claim 8, wherein the diameter of the annuloid shell is not substantially less than its height.

10. A generator according to claim 8 or claim 9, wherein the wave collector is generally toroidal.

11. A generator according to claim 10, wherein the wave collector is formed as an isotorus.

12. A generator according to any preceding claim, wherein said first means is provided with a wave collector comprising a generally hollow canopy having at least one opening for ingress of waves, said canopy having an internal datum level defining a median water level when in use, said at least one opening defining a water inlet area, wherein the ratio of the internal cross-sectional area of the canopy at the internal datum level to the water inlet area is less than 0.7

13. A generator according to claim 12, wherein the generally hollow canopy has a substantially hollow profile.

14. A generator according to claim 12 or claim 13, wherein the upper canopy area is divided into a plurality of cells by a plurality of radial dividers.

15. A generator according to any preceding claim, wherein said first means is provided with a Darius-type rotor.

16. A generator according to claim 15, wherein said Darius-type rotor is provided in a housing having at least one opening for directing an oscillating air flow

onto or away from the rotor in an axisymmetric manner, wherein the rotor comprises a plurality of blades in a substantially catenary shape such that centrifugal loads are substantially balanced by blade tension-forces.

17. A generator according to any preceding claim, gravity anchored to the bed of the sea or other body of water.

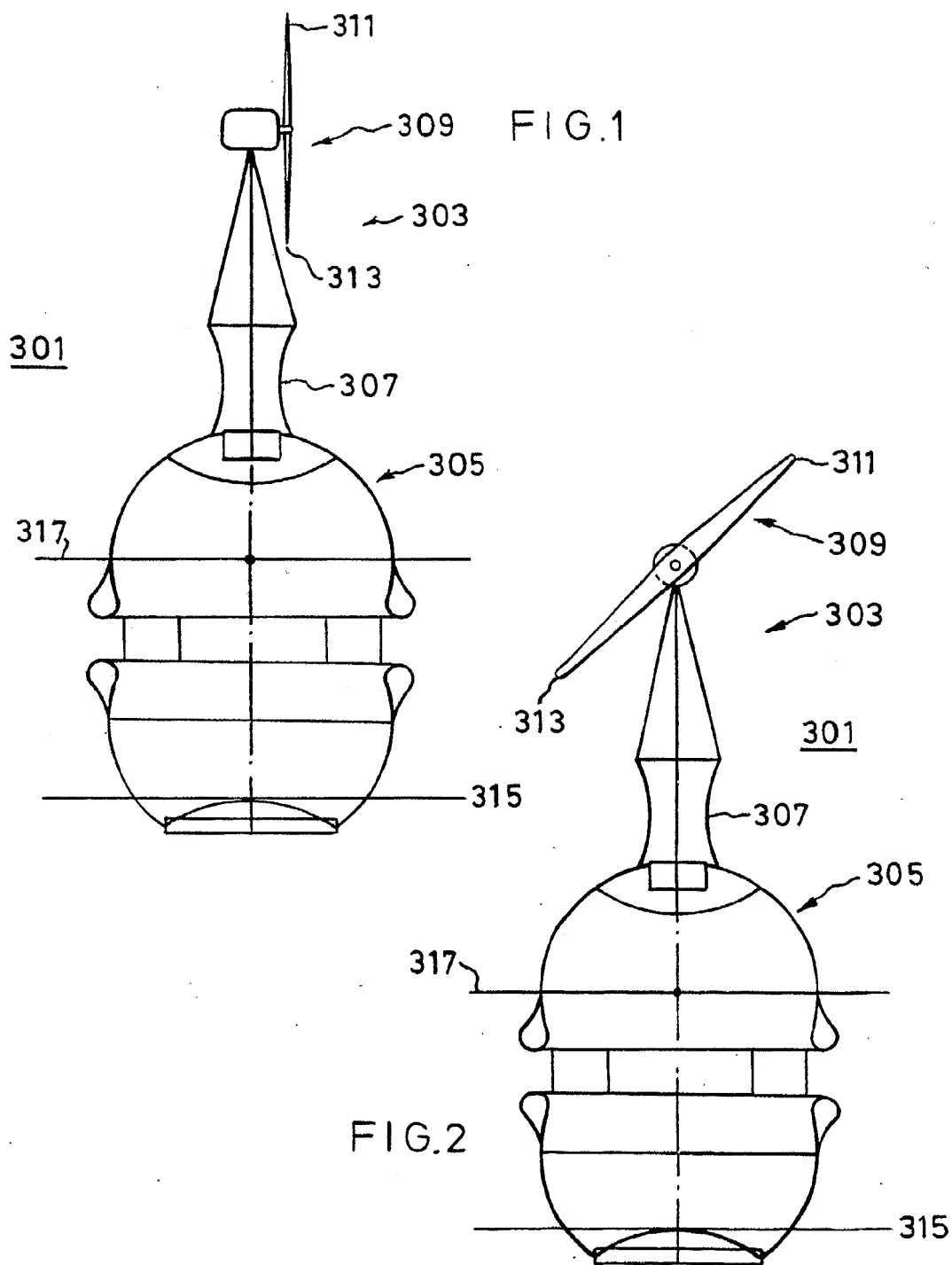
18. A generator according to claim 17, wherein said gravity anchoring is effected by anchoring the generator in and/or with sediments on said bed.

19. A generator according to claim 17, wherein said gravity anchoring is effected by means of a concrete base.

20. A generator according to any preceding claim, wherein said first means is provided with a generally hollow canopy having at least one opening, said canopy being divided internally into a plurality of cells, at least two of said cells having internal dimensions such that the ratio of median waterline cross-sectional area of one of said at least two cells to the median waterline cross-sectional area of the other is in the range of from 3:1 to 1:3.

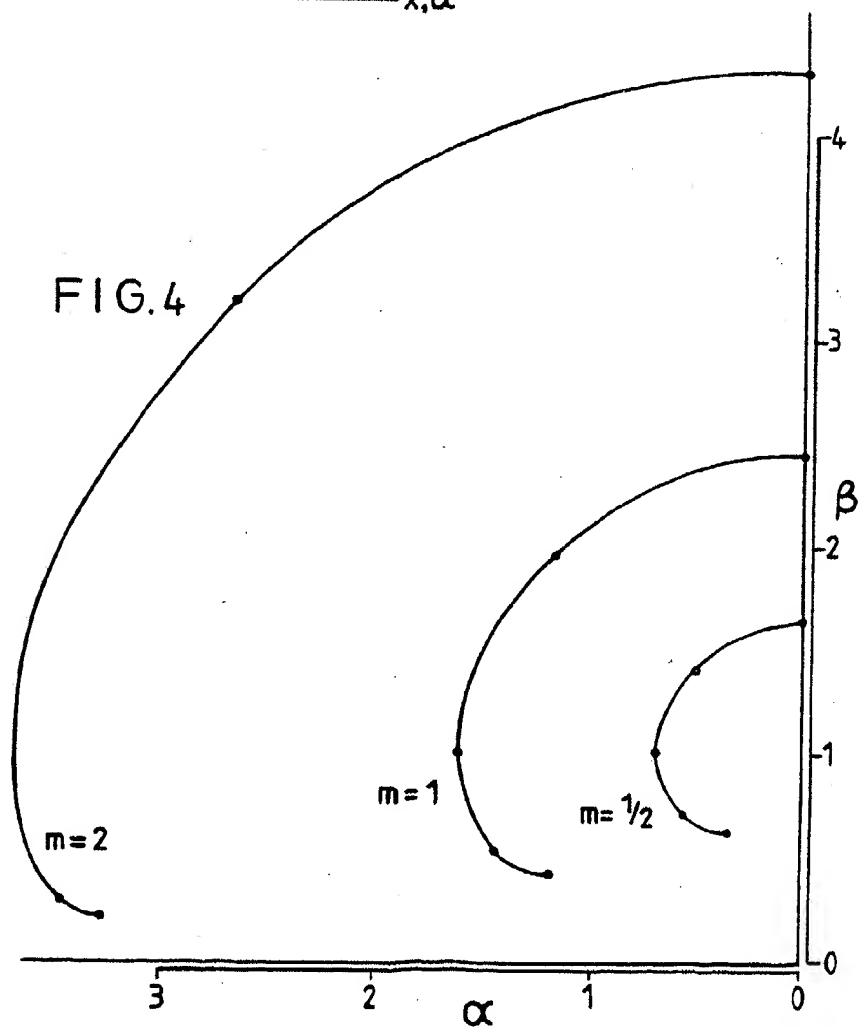
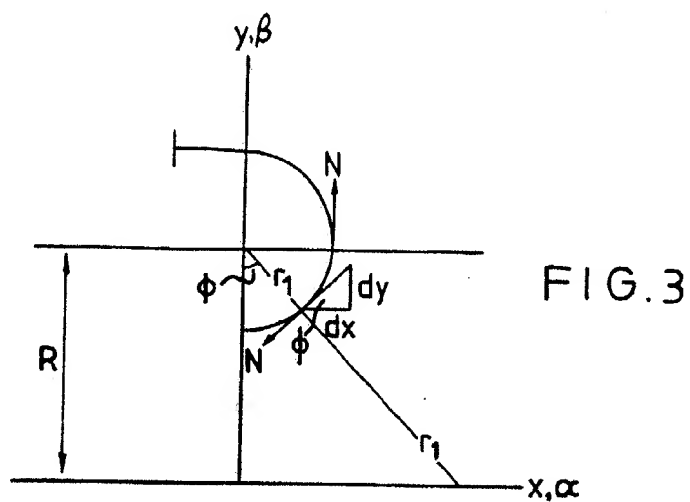
21. A generator according to claim 20, wherein said at least two cells have internal dimensions different from each other.

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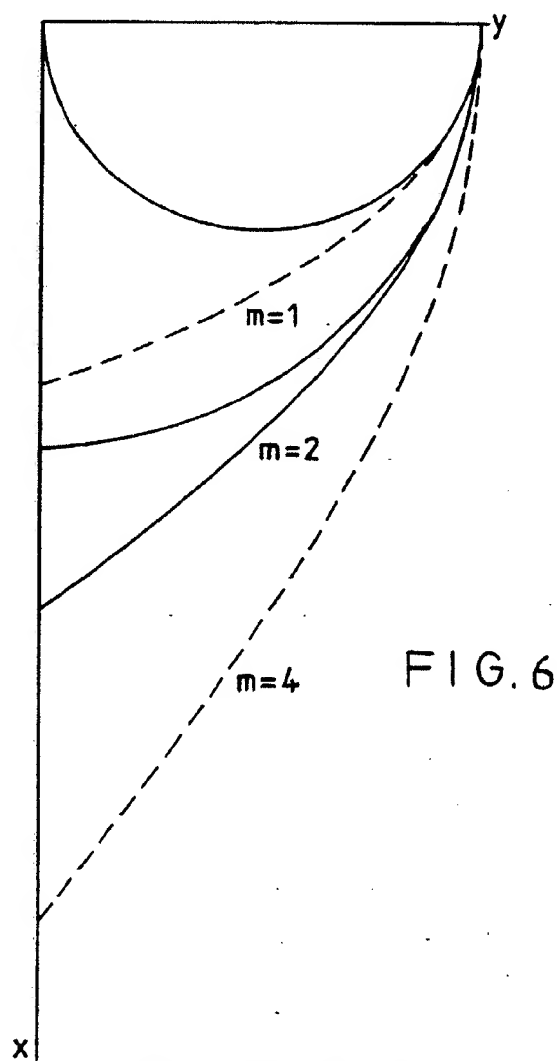
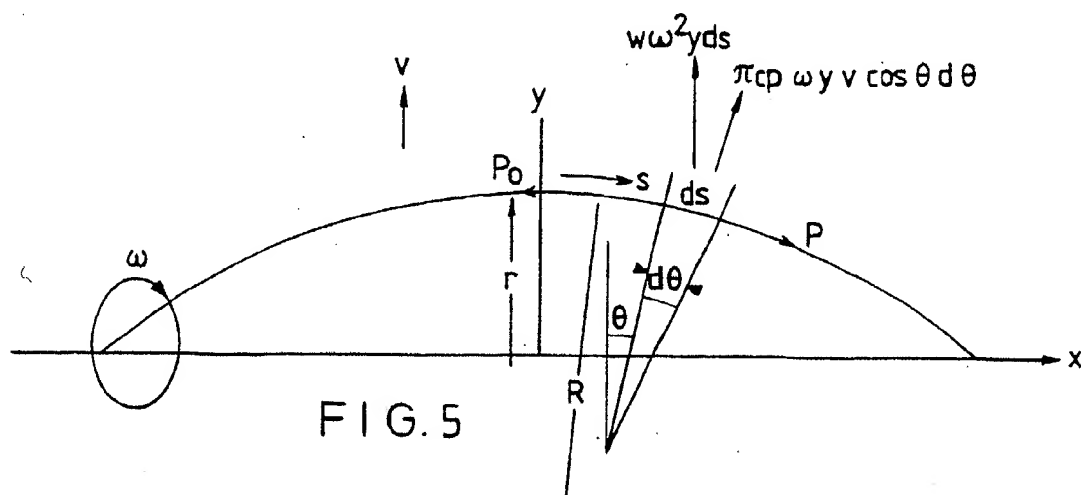
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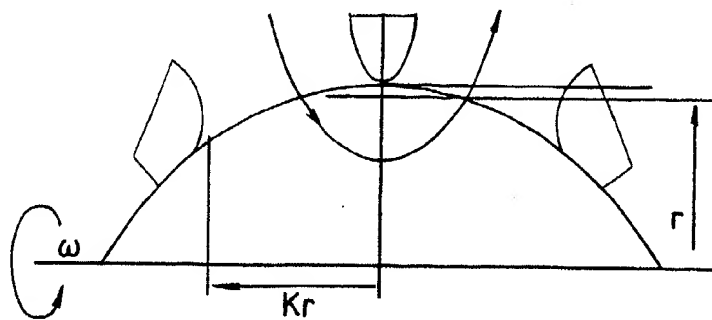


FIG. 7

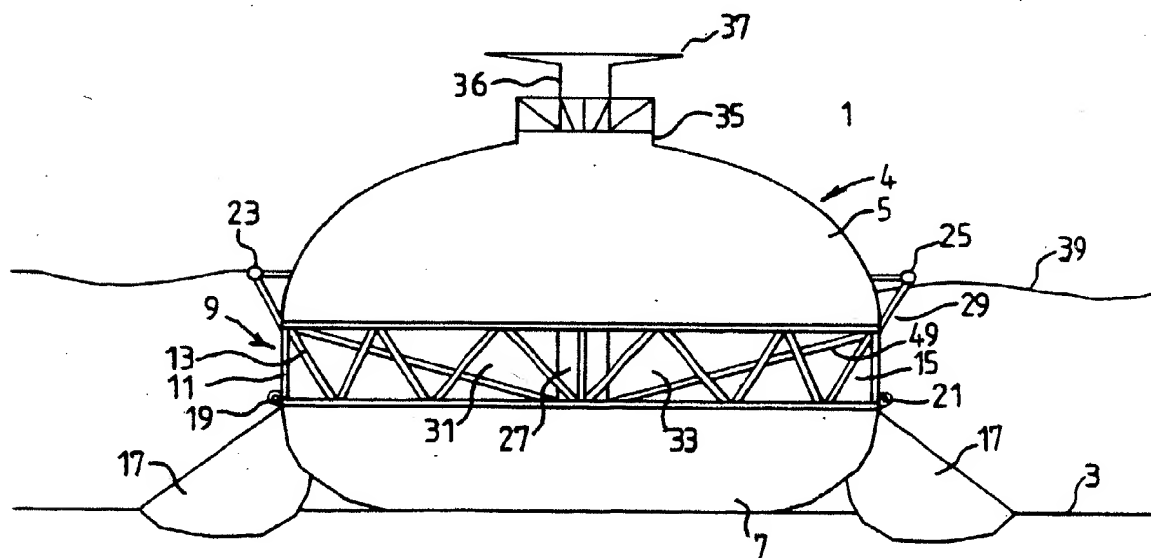


FIG. 8

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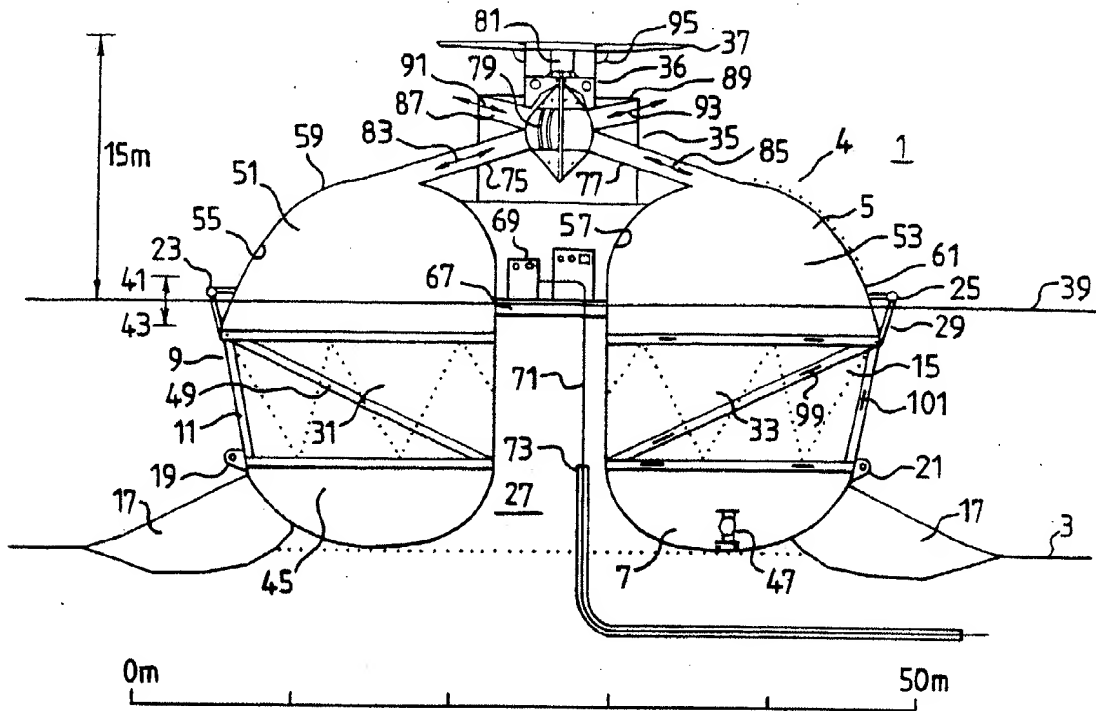


FIG. 9

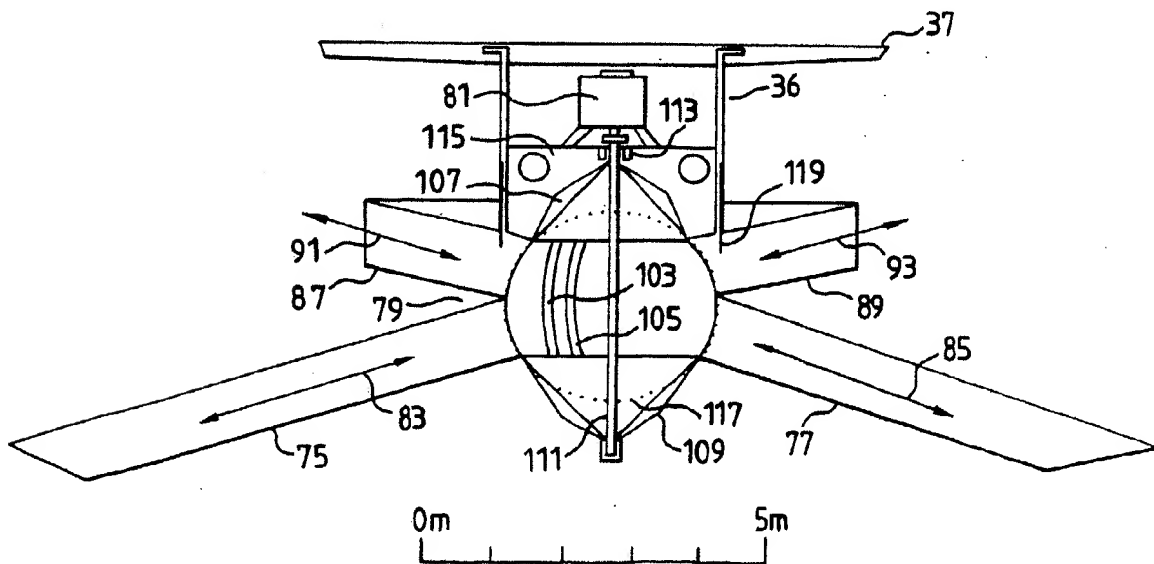


FIG. 10

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FIG. 11

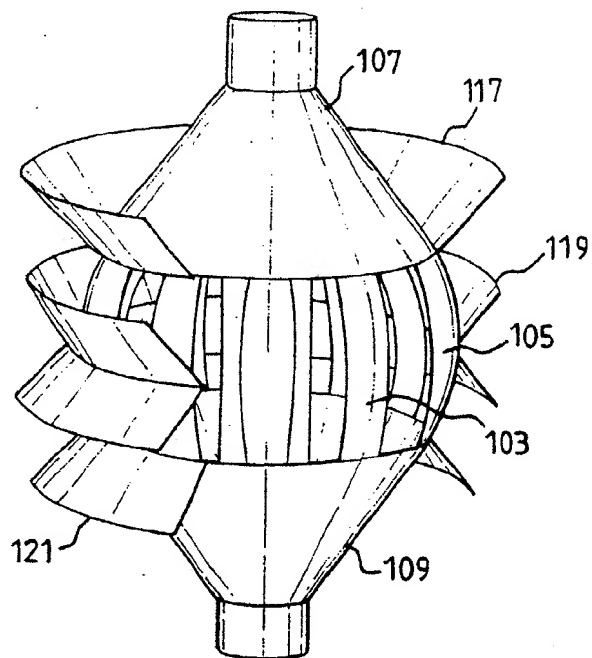
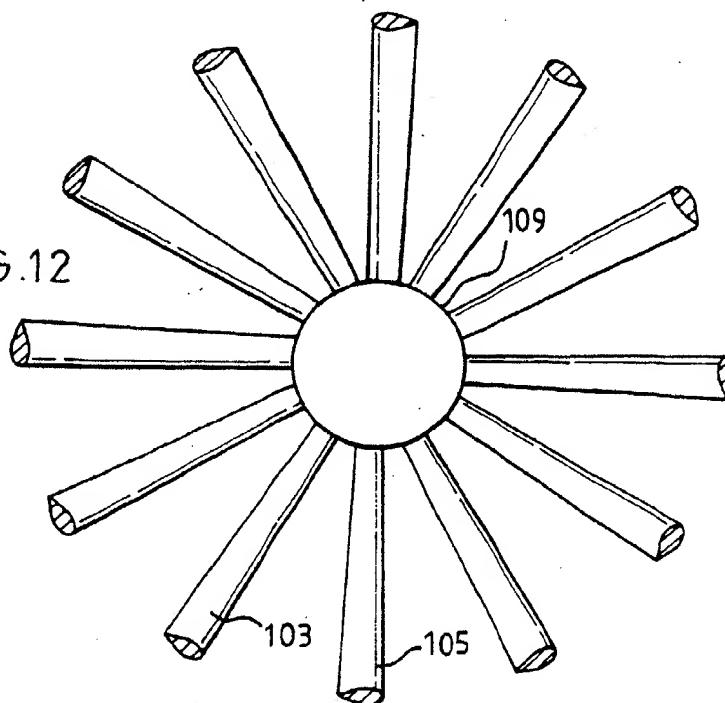
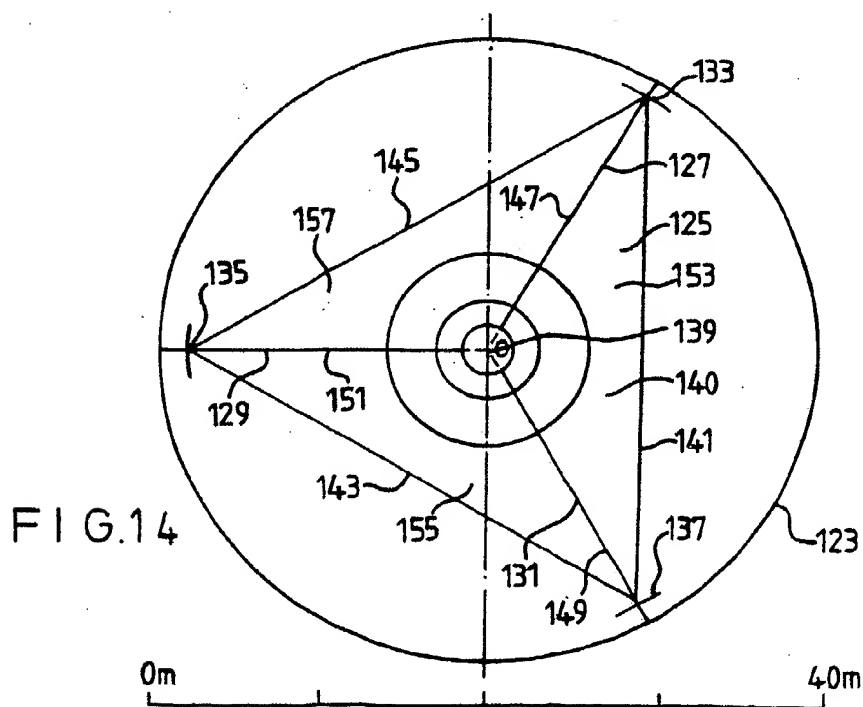
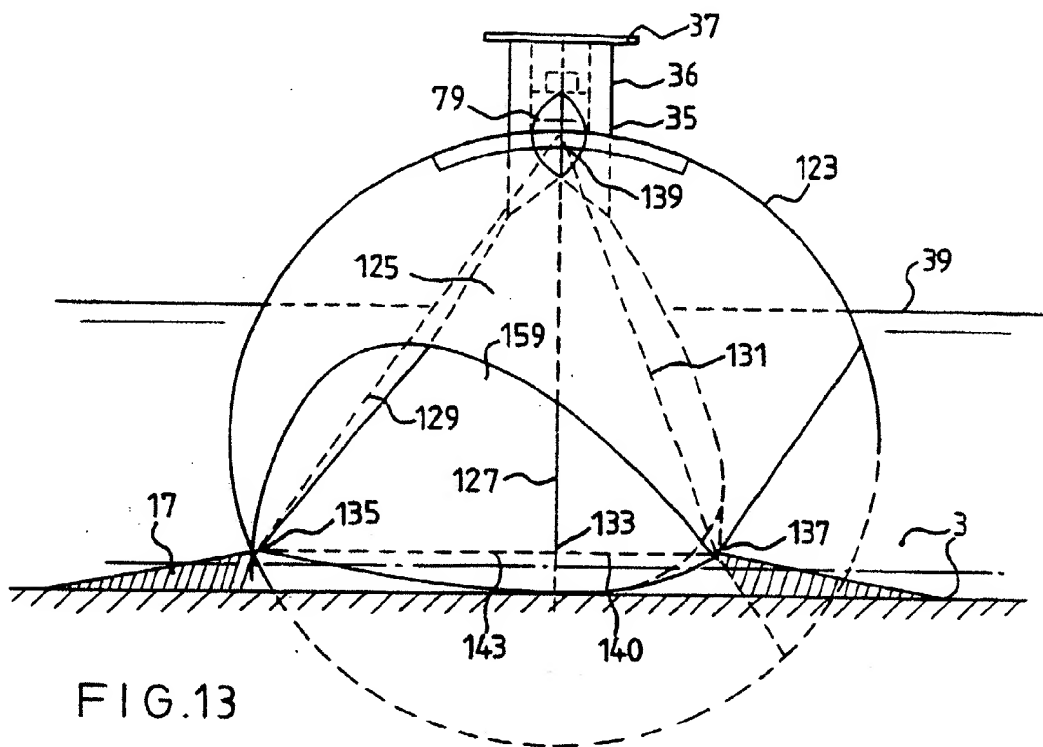


FIG. 12



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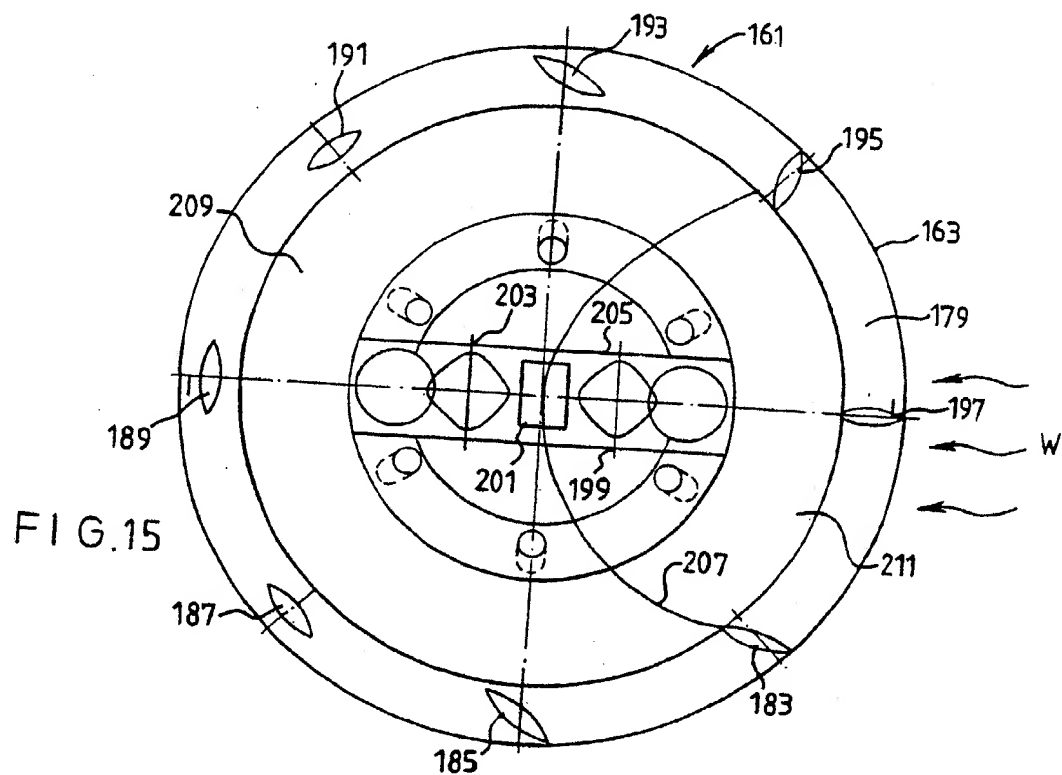
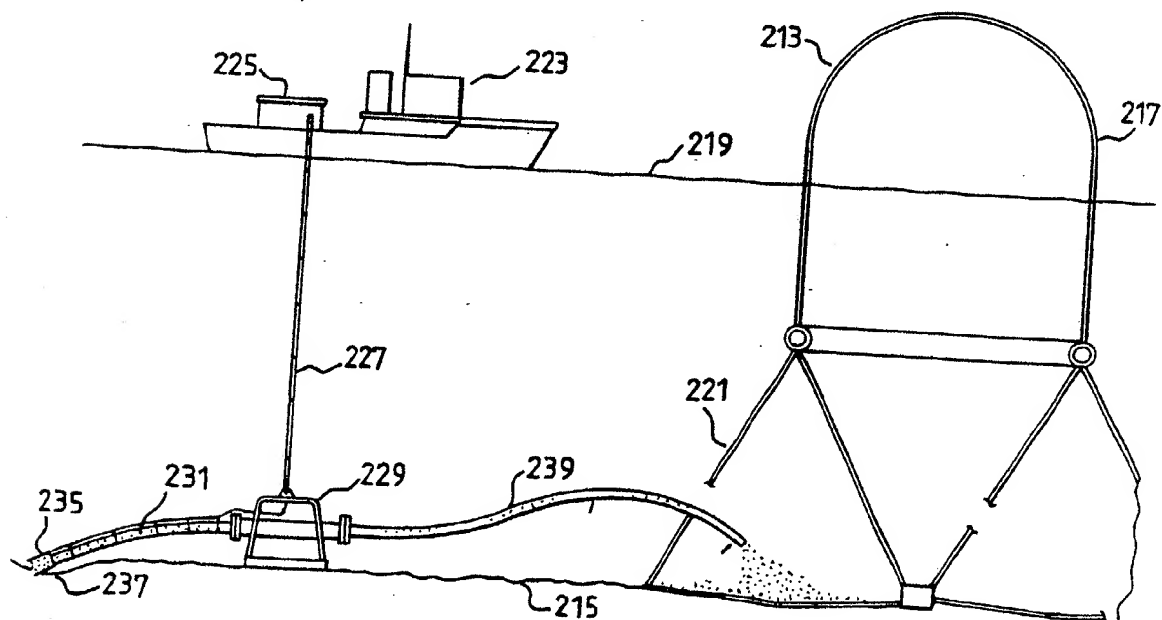


FIG. 17



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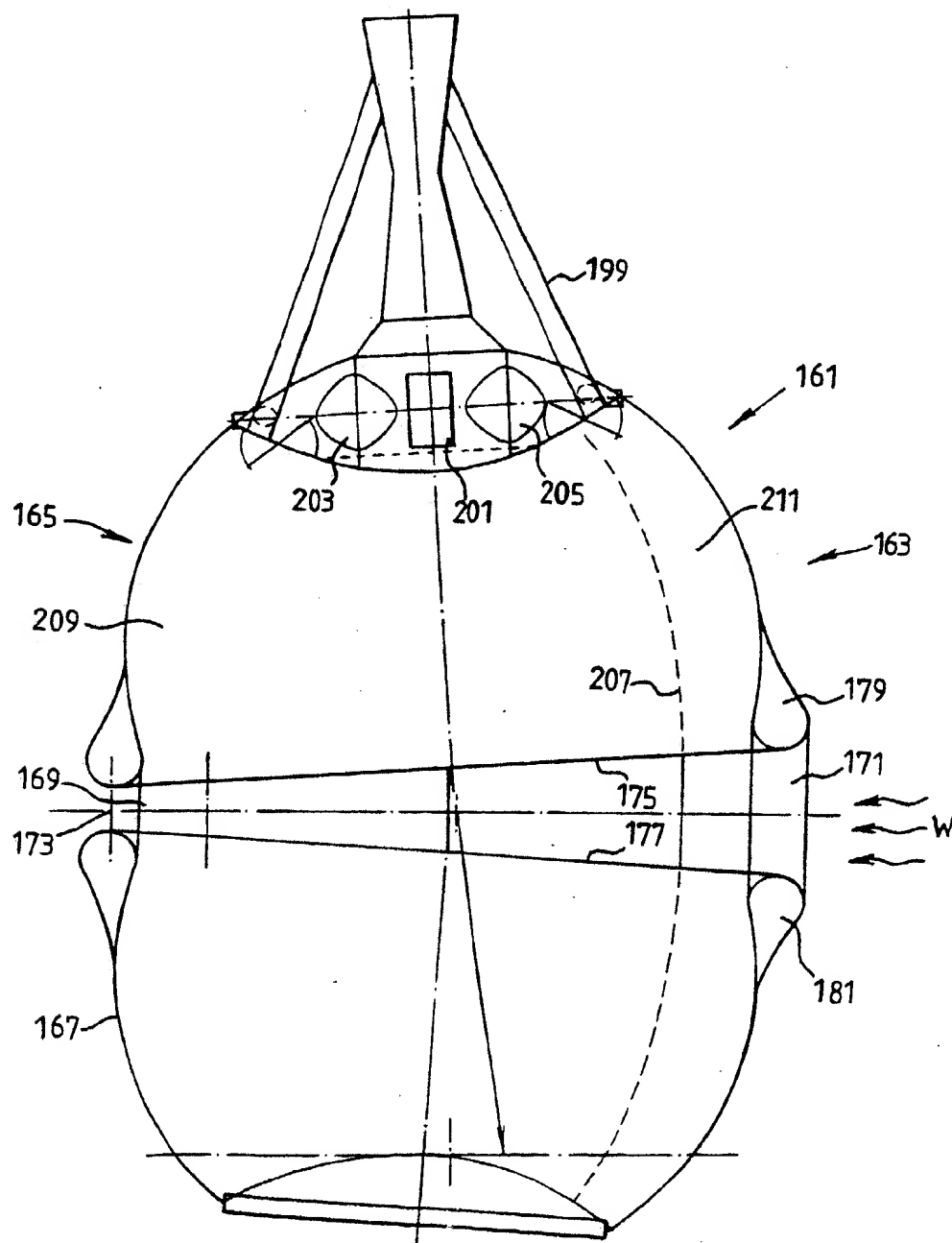


FIG. 16

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 93/02072

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 F03B13/14 F03D9/00 F02C1/02 F03D11/04 F03D3/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 F03D F03B F02C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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| X | DE, A, 38 03 570 (G. ZELCK) 28 July 1988 see column 6, line 23 - line 31; figure 5 see column 7, line 25 - line 27 | 1 |
| Y | | 1-13, 20, 21 |
| Y | | 14 |
| Y | | 15, 16 |
| Y | | 17-19 |
| Y | PATENT ABSTRACTS OF JAPAN vol. 8, no. 274 (M-345) 14 December 1984 & JP, A, 59 145 373 (HITACHI) 20 August 1984 see abstract --- | 1-13, 20, 21 |
| -/- | | |

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

20 December 1993

Date of mailing of the international search report

14. 01. 94

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Authorized officer

Criado Jimenez, F

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 93/02072

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|--|---|-----------------------|
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Information on patent family members

Int. Application No

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| WO-A-9218704 | 29-10-92 | AU-A- 1550792 | 17-11-92 |
| DE-A-3803570 | 28-07-88 | NONE | |
| WO-A-8101174 | 30-04-81 | EP-A, B 0037408 US-A- 4383413 | 14-10-81 17-05-83 |
| AU-B-510185 | 12-06-80 | AU-A- 2093776 | 29-06-78 |
| GB-A-949352 | | NONE | |
| US-A-1835018 | | FR-A- 604390 | |
| FR-A-2370875 | 09-06-78 | DE-A- 2750616 JP-C- 1410057 JP-A- 53092060 JP-B- 62011188 NL-A- 7712434 SE-B- 445756 SE-A- 7712797 US-A- 4221538 | 24-05-78 24-11-87 12-08-78 11-03-87 17-05-78 14-07-86 13-05-78 09-09-80 |
| FR-A-2574130 | 06-06-86 | JP-C- 1691869 JP-B- 3053471 JP-A- 62041974 GB-A, B 2169036 US-A- 4719754 | 27-08-92 15-08-91 23-02-87 02-07-86 19-01-88 |
| US-A-2919552 | | NONE | |
| GB-A-2229476 | 26-09-90 | NONE | |
| US-A-2190003 | | NONE | |
| BE-A-876966 | 01-10-79 | NONE | |